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THE SEISMOLOGICAL EVIDENCE FOR THE TRIGGERING OF BLOCK MOTION BY LARGE EXPLOSIONS

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P.O. Box 1620
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December 1976

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The seismological evidence for the triggering of block motion by large nuclear explosions is ~~summarized and~~ evaluated. While ultimate interest is on the block motion at depth from large surface bursts, the paucity of data for such events makes it necessary to focus on contained explosions. The emphasis is on contained explosions at NTS since most U.S. data are from these events, but the nuclear experiments in Alaska, Colorado, and → next page

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20. ABSTRACT (Continued)

cont. Mississippi are also discussed. The key parameter controlling block motion is found to be the level of tectonic stress in the vicinity of the explosion. It seems unlikely that significant block motions (large relative displacement outside the explosion produced shatter zone) ~~have been~~ were associated with post explosions except within a few hundred meters of the surface where the lithostatic pressure is low. Explosion aftershocks that occur for days after the event can cause block motions at considerable distances from the explosion. A quite cautious upper limit on the associated block motions observed for the megaton event BENHAM is about 50 cm at ranges up to 10 km or so.

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1. INTRODUCTION

Deep underground strategic facilities are to be designed to survive the ground motions due to a specified nuclear surface burst. Cooper (1973) divides the relevant ground motions into early-time and late-time phenomena. The former include the peak stresses, velocities, etc. and have been extensively studied. Much less well understood are late-time phenomena which may also pose significant danger to the hardened facilities; in particular, block motion. "Block motion" occurs when the passage of the explosion-induced stress wave causes differential motion across zones of weakness in the earth. Our intention in this report is to discuss block motion from a seismological point of view.

Relevant to the design and siting of deep underground strategic facilities, there are essentially three questions to be addressed concerning block motion. They are:

1. What is block motion and when does it occur?
2. What are the characteristics that differentiate sites according to their susceptibility to block motion?
3. Having identified the controlling parameters, by what means can we identify the block motion potential of a given site?

Unfortunately, there are little or no data on the situation of direct interest; namely, block motion at depth from large surface bursts. Therefore, we must extrapolate from the data for somewhat different events and use theoretical results.

In the subsequent sections our first purpose is to summarize the seismological evidence for the triggering of block motion by explosions. There is a large body of literature dealing with relevant issues and our approach is to sort through this evidence, organize it and see what conclusions can be drawn.

The emphasis is on the contained underground explosions at NTS, since most of the data is from these events. Our conclusions are summarized in Section 2.6. The format in that section is to list the pertinent questions and to follow with the answers to which we were led by our study.

In Section 3, we attempt to quantify our understanding of block motion. This study has not provided enough information to give estimates of the maximum block motion at a specified scaled range for a large surface explosion in a specified geology. We content ourselves with an estimate of the maximum block motion expected for megaton-size contained explosions. This estimate is simply based on past experience with such events. However, we think we have identified and described the cause of these block motions and the mechanism by which they occur. This is an important step toward being able to extrapolate the results to the problems of direct interest.

Finally, in Section 4, we briefly summarize the questions that have been addressed by this study. We then discuss the important issues that are now unresolved, but could be answered by more detailed study of existing data.

2. SEISMOLOGICAL EVIDENCE FOR BLOCK MOTION

2.1 INTRODUCTION

In this section, we review the seismological literature for evidence of block motion. Our attention is directed to that data having bearing on the problem of direct interest, block motion at depth from large surface bursts.

We will discuss block motion in two distinct categories and the distinction should be made clear at the outset. In the first category are those block motions which occur due to the presence of tectonic stresses in the region of interest. The explosion then triggers release of the tectonic stress by block motion. In the second category are block motions that occur independent of the presence of tectonic stresses. The explosion overpressure causes differential displacements on pre-existing planes of weakness in the rock such as joints, faults and bedding planes. The entire problem, especially the identification of the block motion potential of a given site, is strongly dependent on which type of block motion is assumed to predominate.

There is a plethora of data for past experiments which may be enlightening when studied in the context of the block motion problem. Among the kinds of events to be discussed here are:

> Earthquakes. The most common examples of large scale block motion are earthquakes. Our main interest is in how earthquake faulting can be triggered by explosions.
>
> Contained Underground Nuclear Explosions at NTS. Evidence for the triggering of block motion by these events is fundamental to our study. It is important to understand how much of the apparent block motion is due to peculiarities of the NTS geology. The differences between contained bursts with yields on the order of 1000 KT and the very high yield surface bursts of direct interest must also be taken into account.

Contained Underground Nuclear Explosions Outside NTS. Comparison of these events with the NTS explosions will develop our understanding of those effects that are peculiar to NTS.

Surface and Cratering Explosions. These events are closely related to the surface bursts of direct interest, though the yield is generally much lower. To the extent that information is available, block motion caused by these events is of great interest.

2.2 SPONTANEOUS BLOCK MOTION — EARTHQUAKES

The most common and dramatic block motion is that due to earthquakes. It is generally agreed that earthquakes are the result of a sudden release of tectonic stresses in the earth's crust. The tectonic stress field exhibits wide variations in both amplitude and orientation from place to place within the crust and is continually changing, though at widely varying rates. When the local tectonic stresses increase beyond the cohesive strength of the crustal rock, an earthquake occurs. In the simplest sense, foreknowledge of earthquake-induced block motion requres two pieces of information: (1) the character of the tectonic stress field, and (2) the cohesive strength of the rock.

As far as explosion-induced block motion is concerned, we conclude that earthquake-like block motion will occur if either (1) the explosion induced stress field adds to the tectonic stress with the total being sufficient to initiate faulting, or (2) the explosion reduces the cohesive forces by an amount sufficient to allow faulting to begin.

The reduction of cohesive forces and consequent triggering of earthquakes can be done by increasing the pore pressure in the rock. The hypothesis is that increased fluid pressure reduces the effective normal stresses and therefore the

static frictional forces on fault surfaces. The validity of this hypothesis has been demonstrated by the earthquake control experiment at Rangely, Colorado (Raleigh, et al., 1976), where variations in earthquake frequency were produced by variations in the fluid pressure in the vicinity of the fault zone in which the earthquakes occurred. Ample evidence for the importance of pore pressure variations in earthquake triggering is available for other events. For example, see the report by Bufe, et al. (1976) on the 1975 Oroville earthquake.

Explosion-induced waves are primarily compressive. However, after passage of the main compressive portion of the wave, a substantial tensile wave is usually observed. This tensile portion of the wave may also act to reduce the cohesive forces on the fault, allowing faulting to begin.

2.3 BLOCK MOTION ASSOCIATED WITH UNDERGROUND NUCLEAR EXPLOSIONS AT NTS

The seismologic and geologic evidence for block motion associated with underground explosions may be divided into four categories:

1. Observations of surface faulting.
2. Far-field ground motion recordings.
3. Near-field ground motion recordings.
4. Studies of aftershock activity.

All these data give clear evidence that the explosion is accompanied by large asymmetric effects. However, the nature of the mechanism for these higher order effects has been a subject of debate for many years. In this section, we will summarize the evidence gleaned from a large number of sources.

Almost from the beginning of the underground test program in Nevada it was noticed that the induced ground motion had many characteristics in common with that from naturally occurring

earthquakes. Both SH body waves (horizontally polarized shear waves) and Love (surface waves with horizontal particle motion) waves were commonly observed. The Rayleigh waves were found to have a non-circular radiation pattern. The history of the early attempts to explain these observations is concisely summarized by Aki and Tsai (1972). It is now agreed that the far-field data can only be explained by assuming that superimposed on the center of dilatation explosion source is a double-couple source. The double-couple is, of course, the simple point source representation of an earthquake.

Having agreed that there is a significant source of earthquake-like ground motion associated with NTS explosions, the next task is to understand the mechanism for its generation. It is generally agreed that the mechanism is some form of tectonic stress release and some of the evidence leading to that conclusion will be discussed subsequently. In any case, the obvious conclusion for our purposes is that, at least at NTS, large underground nuclear explosions are commonly associated with some kind of block motion. The questions are, how large is this block motion and how far from the explosion does it occur? These questions will be kept in mind in the discussion to follow.

Underground nuclear explosions have often been observed to trigger movement at the ground surface on nearby faults. These observations may be of great importance for understanding explosion-induced block motion. McKeown and Dickey (1969) summarize the USGS studies of these fault displacements that were carried out between 1966 and 1969. They mainly discuss the large Pahute Mesa events, BOXCAR, GREELEY and DURYEA, as well as the FAULTLESS event in central Nevada. The important conclusions of this study are as follows:

1. The permanent vertical displacement on the faults was always in the same direction as the last

recognizable natural tectonic displacement and was as much as one meter.

2. Horizontal movement was also triggered, ranging up to 15 cm.

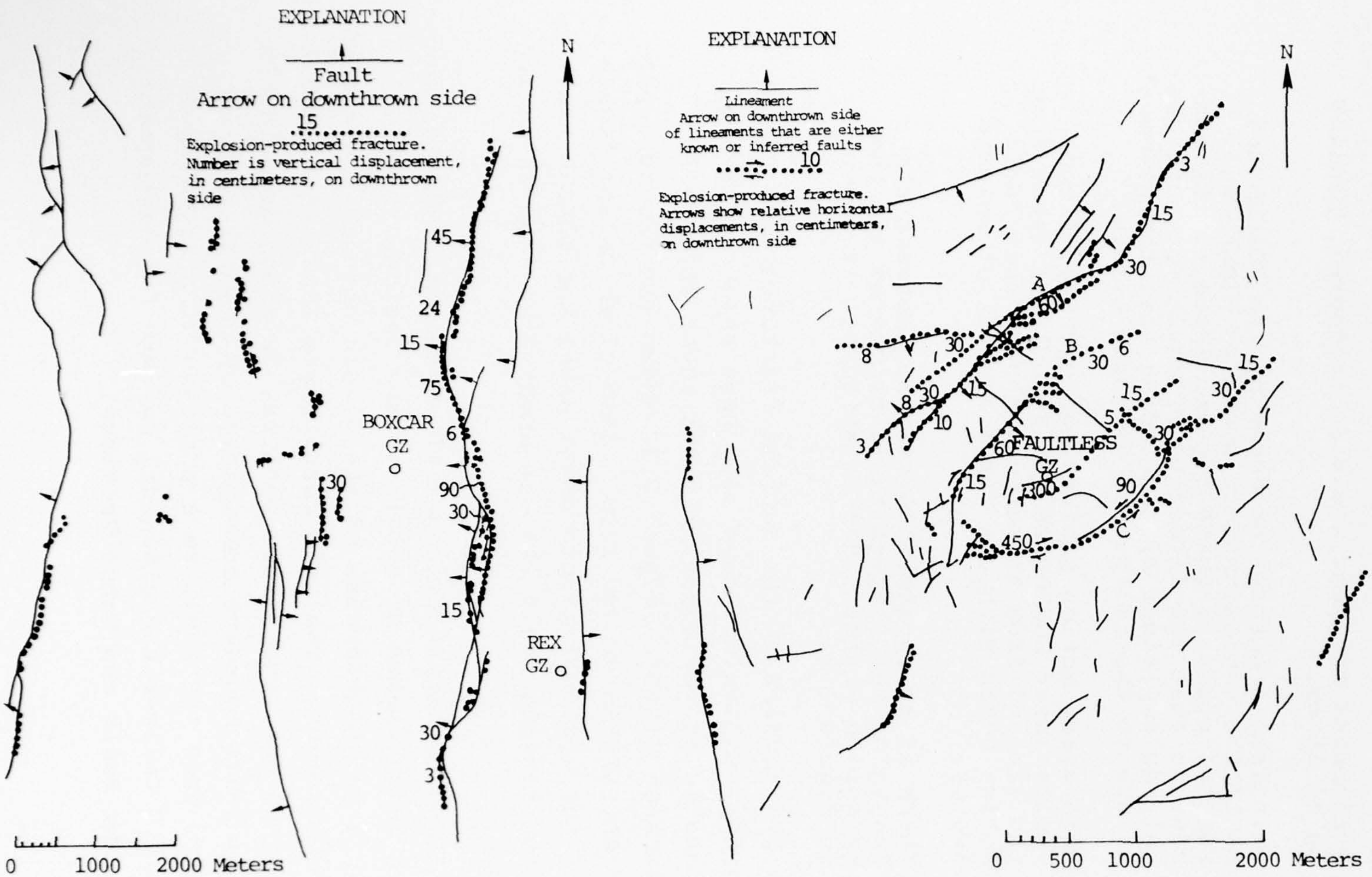
3. Principal fractures produced by the BOXCAR and FAULTLESS explosions are shown in Figure 2.1. Careful study of these figures leads to the conclusion that the direction of fault movement can only be explained by concluding that the movement is due to the release of tectonic strain.

4. High speed motion picture photography of two faults (near COMMODORE and FAULTLESS) taken from the air and from the ground showed that fault motion began with the first arrival of seismic energy.

5. There is an apparent correlation between the length of the longest fault triggered and the explosion yield. This relationship is shown in Figure 2.2.

Detailed studies of the surface fracturing associated with underground explosions have also been reported by other authors. Notable is the description of these effects for BENHAM by Bucknam (1969). Figure 2.3. shows the fracture pattern around the BENHAM ground zero. Also given in the figure is a plot of the vertical displacement along the BOXCAR fault, a north-south trending fault that is about 2 km from GZ at its closest point.

The direct geologic evidence of surface faulting is consistent with measurements of strain in the region. Dickey (1969) reports on measurements of the strain changes associated with the BENHAM event. The main results are shown in Figure 2.4. As Dickey points out, the strain pattern, "a sharp drop in elevation at the fault boundary accompanied by gradual rise in elevation away from the fault to a position of sharp drop at another fault," follows the classical pattern for earthquake faulting in the Basin and Range Province.



a. Fractures produced by the BOXCAR explosion, Pahute Mesa, Nevada Test Site. Faults after Orkild, et al. (1969).

b. Fractures produced by the FAULTLESS explosion, Hot Creek Valley, central Nevada.

Figure 2.1. Fractures of two large underground explosions (from McKeown and Dickey, 1969).

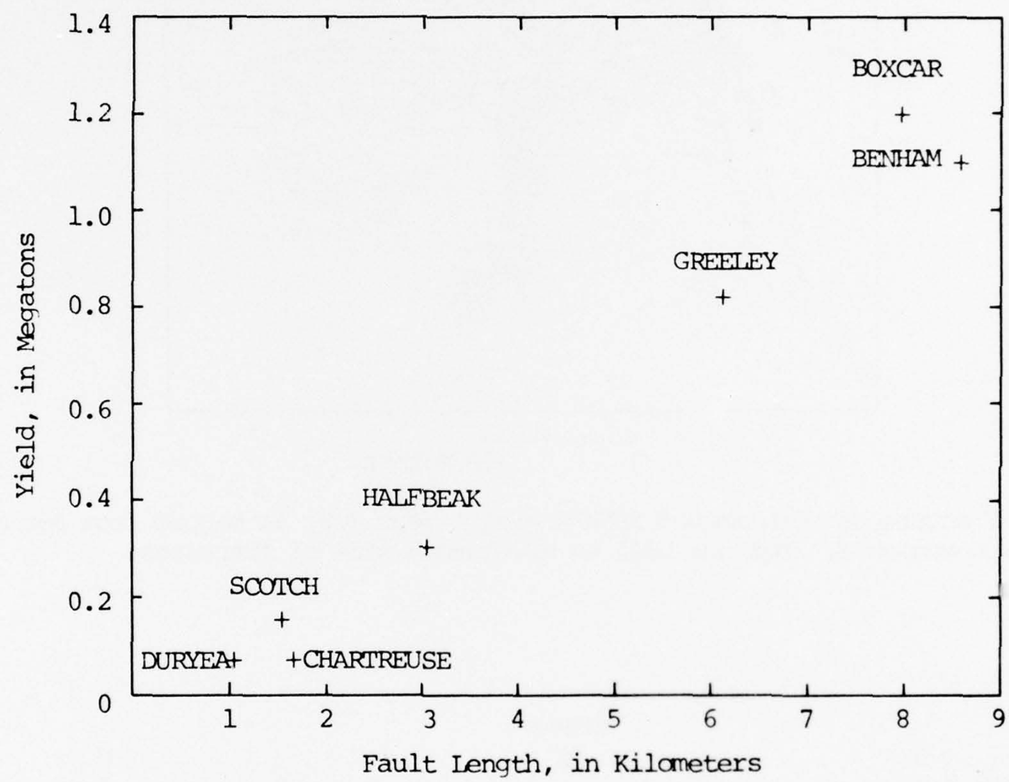
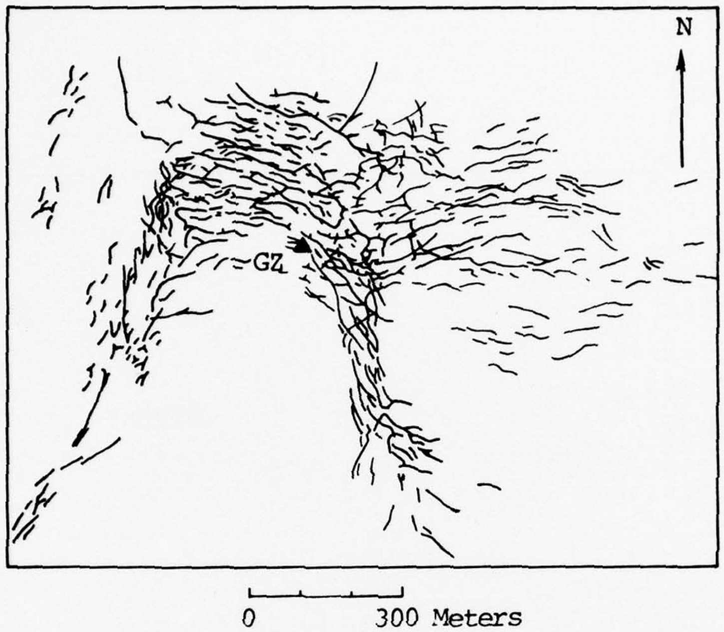
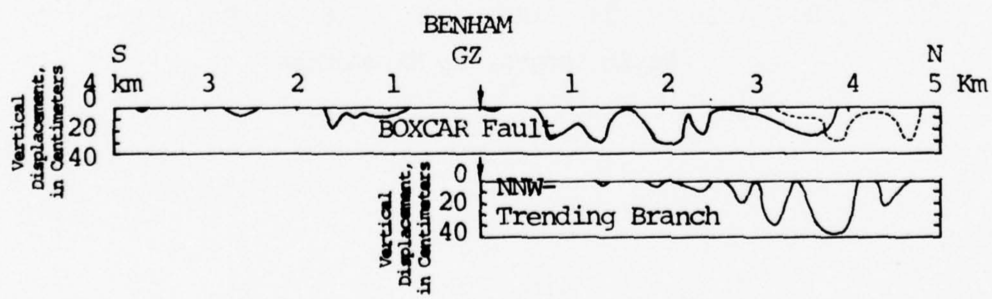


Figure 2.2. Relation of fault length to yield of nuclear explosions in Pahute Mesa, Nevada Test Site (from McKeown and Dickey, 1969).



a. Fracture pattern around BENHAM ground zero (GZ) as mapped from aerial photographs. Bar and ball on downthrown side of fractures.



b. Vertical displacements on the BOXCAR fault and its north-northwest-trending branch projected onto N-S plane. Solid line represents displacements due to the BENHAM event; dashed line, those due to the BOXCAR event.

Figure 2.3. Fractures in the vicinity of BENHAM (from Bucknam, 1969).

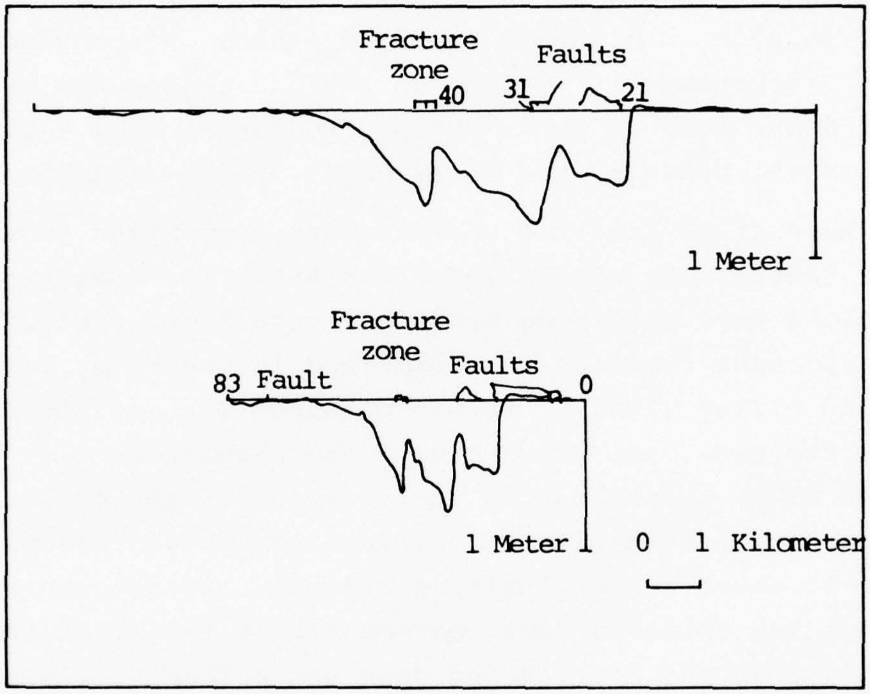


Figure 2.4. Level line showing changes resulting from BENHAM event. Pre- and post-explosive elevations are recorded by straight and irregular lines, respectively. Top diagram is along devious route of level line. Bottom diagram represents projection of points to a straight line between end stations of the level line (from Dickey, 1969).

Bucknam (1972) looked at the (static) vertical displacement associated with HANDLEY and found it to be qualitatively similar to that from BENHAM. Once again, the surface deformation was at least superficially consistent with that for classical Basin and Range faulting. In his 1972 paper, Bucknam uses this data in an attempt to place bounds on the depth of faulting and the fault dislocation. He concludes that the displacement triggered on the fault does not extend to great depth but, at most, extends to depths of 1 - 2 km (depths on the order of the focal depth of the explosion).

The surface faulting observations summarized above were for Pahute Mesa events and FAULTLESS. The same kind of observations have also been made for Yucca Flat events. Many of the important results are summarized in papers by Barosh (1968) and Dickey (1968). Barosh observes that on the major fault in the area, the Yucca Fault, the displacement is always east side down, regardless of the location of the explosion. This is a clear indication of the involvement of regional tectonic stresses in the faulting process. Both authors conclude that the observed fault movement is a result of fault displacement in the bedrock and does not reflect differential compaction of the overlying alluvium.

Dickey (1968) plotted the explosion yield versus the minimum distance of ground zero from the Yucca Fault. This plot is shown as Figure 2.5. All the explosions causing displacement were within a scaled (to the cube root of the yield) distance of 1000 feet from the fault. The scaled distance to the farthest point of fractures along the Yucca Fault ranged from 920 to 3600 feet for seventeen events that were mapped in detail. The same kind of analysis for the Area 3 fault found that the scaled distances were about half as large for displacements to occur on this fault. Finally, Dickey (1968) concluded that the fault displacement is greatest for the first event

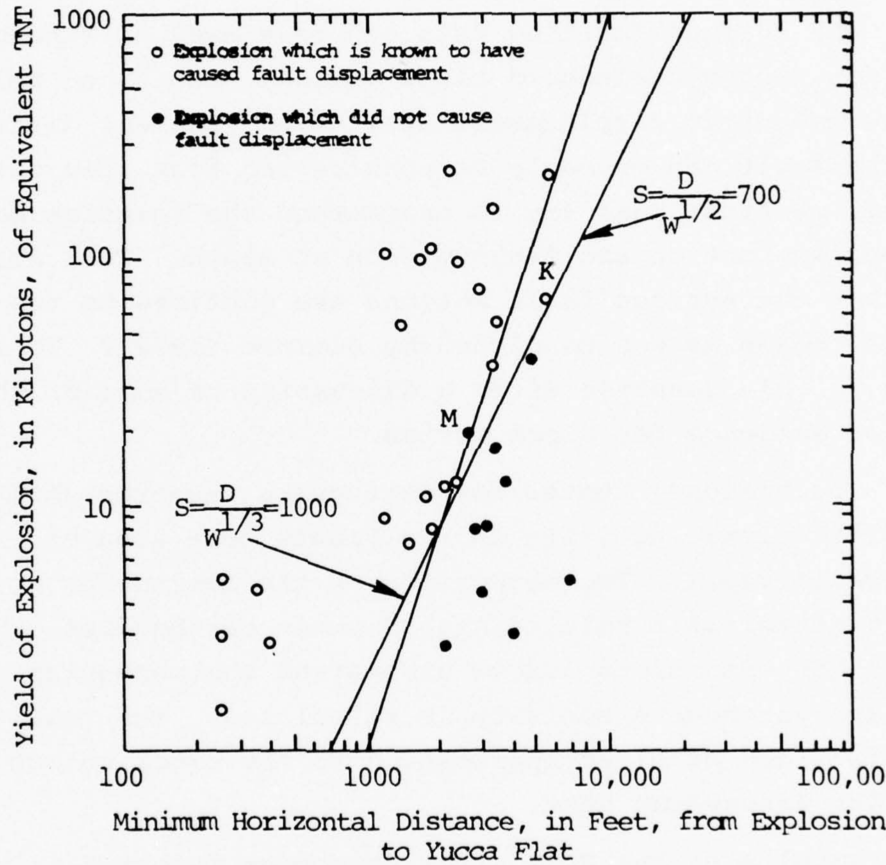


Figure 2.5. Plot of yield of underground explosions near Yucca fault versus their horizontal distance from the fault (from Dickey, 1968).

detonated near the fault and is less thereafter. This is again consistent with the hypothesis that release of tectonic stress is res[illegible]sible for the fault displacements. That is, the time sca[illegible] buildup of tectonic stress along these faults is qui[illegible]mpared to the time between explosions.

The surfa[illegible]ting data can be viewed as strong evidence for explosion-induced block motion. Empirical relations for the amount of displacement at a given (scaled) distance from the fault can probably be constructed from this data. However, we first must try to understand the relation between this surface motion and fault motion at depth. That is, is it true that the surface fault motions are confined to the near-surface region as was concluded by Bucknam (1972)? We shall return to this question after a discussion of some of the other kinds of evidence for block motion.

The National Center for Earthquake Research (NCER) monitored seismic activity in the Pahute Mesa area of NTS for several years. Two objectives of the monitoring program were to establish a relationship between earthquakes and underground explosions and to understand the mechanism by which the earthquake activity is stimulated. The results of this study are of clear application to the block motion problem under discussion here.

Results of the NCER study have been reported in a number of articles including Hamilton and Healy (1969), Hamilton, et al. (1969) and Hamilton, et al. (1972). The latter study states several conclusions of considerable interest here and these are repeated below together with a few comments regarding supporting data from other sources.

1. Aftershock sequences were initiated by the events BENHAM, PURSE, JORUM and HANDLEY.

2. Ninety-four percent of the earthquakes (in the aftershock sequences) that had well-determined focal depths were shallower than 5 km.

3. Ninety-five percent of the located earthquakes were within 14 km of ground zero of the preceding explosion. There is no evidence for explosion-stimulated earthquake activity extending outside Pahute Mesa.

4. Part of the BENHAM aftershock zone was active before detonation of BENHAM. This activity could be aftershocks of BOXCAR.

5. PURSE reactivated much of the BENHAM aftershock zone.

6. PIPKIN had essentially no effect on seismicity, even though it was in the same region. Hamilton, et al., suggest that this may be due to the fact that PIPKIN was above the water table while the other shots studied were below. A more likely cause may be the fact that PIPKIN was detonated near the earlier megaton events BOXCAR and BENHAM. These two larger events may have already released much of the tectonic stress around the PIPKIN emplacement.

7. HANDLEY caused earthquakes in a new area and stimulated activity in areas affected by earlier explosions.

8. Early aftershock activity of BENHAM, JORUM and HANDLEY were predominantly near the shots (within about 2 km), with the more distant activity beginning after cavity collapse. Perret (1971) used more accurate instrumentation to look at the early JORUM after-events and found similar results. In fact, the major (largest) after-events were located within 100 meters of the cavity.

9. The epicenter distribution can be associated with observed surficial fault movement only for aftershocks of HANDLEY.

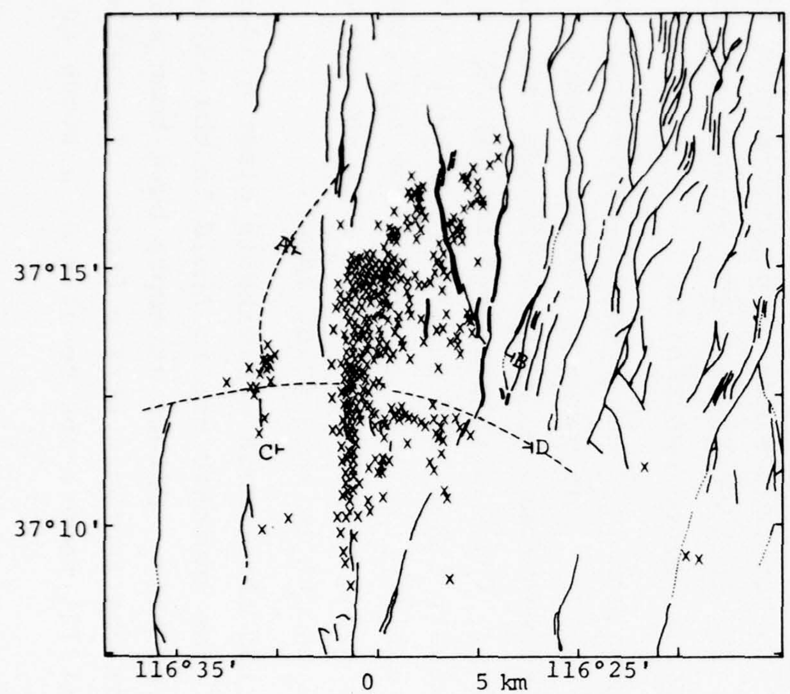
10. Fault-plane solutions indicate predominant dip-slip movement in the northern part of the Pahute Mesa area for aftershocks of BENHAM, JORUM and HANDLEY. In the southern part, right-lateral strike-slip movement was found for aftershocks of BENHAM and HANDLEY. The tension axis is consistently oriented west-northwest in agreement with the regional stress field.

11. Seven relatively small explosions in the southeastern part of the area studied (WINESKIN, DIANA MIST, MINT LEAF, HUDSON MOON, DIESEL TRAIN, CYPRESS and DIAMOND DUST) had no apparent effect on seismicity.

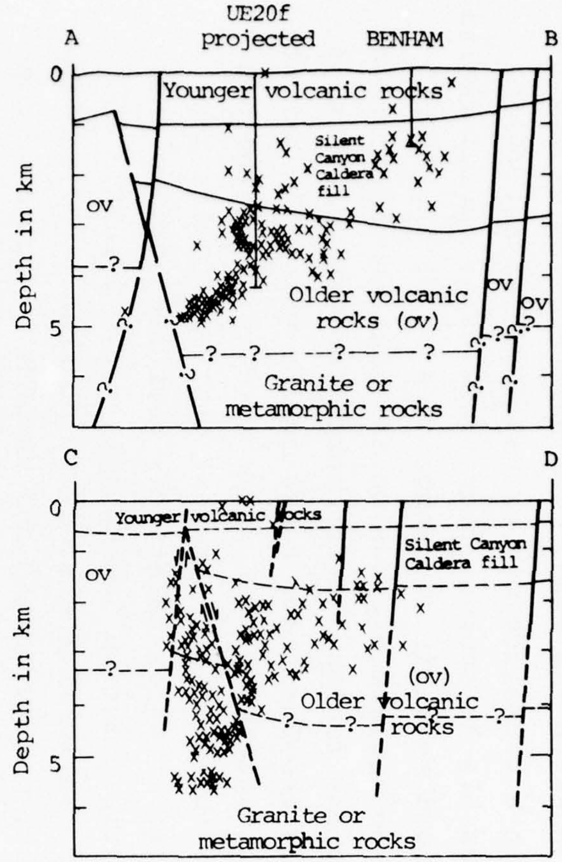
How do these conclusions relate to the observations of surficial faulting? Six of the seven small explosions that had no effect on the seismicity (conclusion 11 listed above) were at Rainier Mesa. Dickey (1968) pointed out that the RAINIER, LOGAN and BLANCA explosions on Rainier Mesa caused no observed surface displacements on known nearby faults. These two facts are consistent in indicating a relatively low level of block motion at Rainier Mesa.

Of great significance for our study is the conclusion number 9 listed above. If the observed surficial fault movements at Pahute Mesa were associated with fault movements at depth, we would expect (based on our experience with natural earthquakes) considerable aftershock activity along the fault. With the possible exception of HANDLEY, this is not the case. This conclusion is graphically illustrated in Figure 2.6 taken from the study by Hamilton and Healy (1969) of the BENHAM aftershocks. The zone of major aftershock activity lies a few kilometers to the west of ground zero while most of the surface fault movement was on faults to the east of the hypocenter. Only a few aftershocks occurred near the faults on which the major surface faulting occurred.

The lack of correlation between surface faulting and aftershock activity is disappointing because it makes the development of empirical relationships for block motion associated with large explosions much more difficult. There have been attempts to explain this anomaly (at least it is anomalous compared to our understanding of natural earthquakes). McKeown (1975) attempted to integrate all available geologic seismologic data to understand the relation between faults and aftershock



a. Map showing earthquakes (X) and fractures (thick lines) caused by BENHAM (solid circles), faults (thin lines), caldera boundaries (dashed lines), and lines of vertical section for Figure 2.6b (A, B and C, D).



b. Vertical sections across BENHAM seismic zone showing earthquake (X) distribution and generalized geologic structure. Geologic structure prepared by F. A. McKeown (written communication). No vertical exaggeration. Hypocenters projected lie within 1.23 km of plane A-B or within 2.45 km of plane C-D.

Figure 2.6. Spatial distribution of BENHAM aftershocks (from Hamilton and Healy, 1969).

activity. He concludes that the aftershocks are associated with what he calls "ring fractures" that are related to the calderas buried beneath the mesa. The same conclusion was earlier stated in a tentative way by Hamilton, et al. (1969). It is quite plausible to suppose that there exist buried faults (of the north trending Basin and Range type or of the "ring" type) that have no surface expression and that the aftershocks occurred along these faults. Left unexplained is the lack of aftershocks along the Basin and Range faults which did exhibit large surface displacements. It seems hard to avoid the conclusion that the observed displacement on these faults was indeed confined to a region relatively near the surface where the low lithostatic pressure undoubtedly plays a part. In fact, we earlier mentioned the study by Bucknam (1972) of the vertical deformation from BENHAM and HANDLEY in which he concluded that the observed fault displacements were confined to a region within 1-2 km of the surface. Assuming this to be true, Bucknam points out that since most after shocks occur at depths of 1-5 km, the lack of correlation between aftershocks and surface fractures is not surprising.

Let us now return to another conclusion listed by Hamilton, et al. (1972); that given as number 8 above. The aftershock activity was found to migrate outward from the epicenter with time. This is illustrated for BENHAM in Figure 2.7, once again taken from Hamilton and Healy (1969). The migration of activity is also important for deducing the mechanism for the block motion associated with the NTS explosions and we will return to this point later.

Certainly the aftershock activity is clear evidence of a readjustment of the tectonic strain field in the vicinity of the explosion hypocenter. Direct attempts have been made to monitor changes in the tectonic strain field. In particular, Lee and Nichols (1972) report the results of a study in which

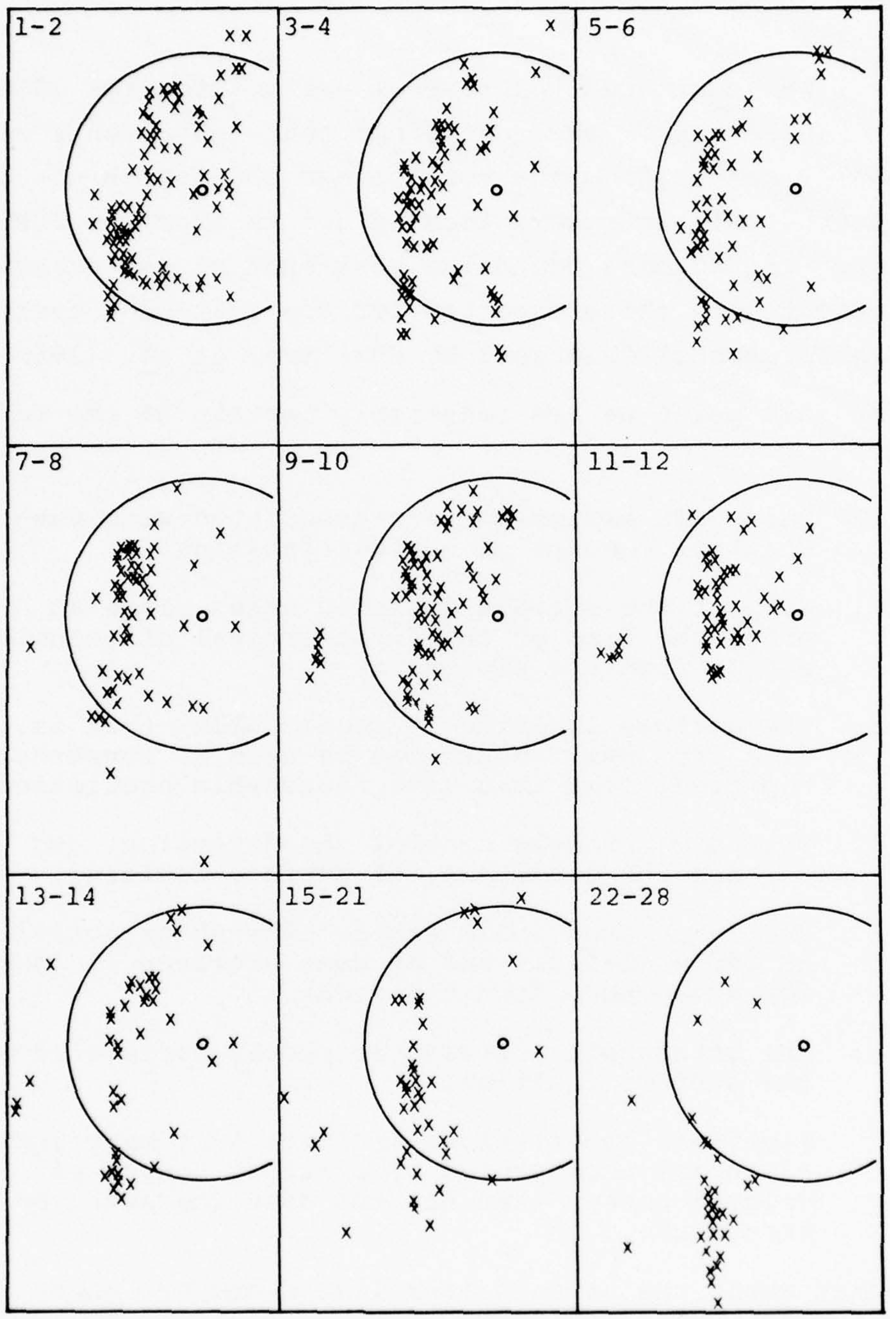


Figure 2.7. Epicenter maps showing the migration of seismic activity following BENHAM. The circle in each case has a radius of 5 km and is centered on BENHAM ground zero. Numbers refer to days after detonation. Three epicenters southeast of ground zero are now shown (from Hamilton and Healy, 1969).

the stress was monitored for several weeks after the JORUM event at Pahute Mesa. Three of their four instruments were less than 10 meters from the surface and the fourth was at 1.2 km depth. All four were located 3-9 km from the JORUM epicenter. The authors found the post-shot stress changes to be consistent with those expected for the post-shot earthquakes (aftershocks) described by Hamilton, et al. (1969).

At this point we are reasonably certain of the following facts:

1. Large NTS explosions are associated with substantial amounts of surface faulting.

2. Much of the surface faulting takes place at about the time of the first arrival of seismic energy from the explosion.

3. The surface faulting is predictable; that is, data from past events can be used to construct empirical laws that give reasonable predictions.

4. Tectonic stresses control the direction, and perhaps the amplitude, of surface faulting.

5. The large explosions excite aftershock activity at depth (1-5 km) and at some distance ($\approx$ 14 km for a megaton) from the event.

6. The aftershock activity is poorly correlated with the surface faulting.

7. Far-field observations indicate that many explosions are accompanied by a strong source of seismic energy that has the same character as an earthquake.

What about the seventh item listed above? Where does the earthquake-like energy come from? The clear far-field evidence of earthquake-like ground motion accompanying the explosion together with the surface faulting and aftershock evidence (though not their lack of correlation) has led a number of seismologists to conclude that earthquakes are commonly, or at least sometimes, triggered by NTS explosions.

The most important papers advancing this conclusion are probably those by Aki, et al. (1969) and Aki and Tsai (1972). These authors postulate fault lengths on the order of 10 km for the megaton shots BOXCAR and BENHAM. They further suppose the faulting to extend from the surface to a depth of 5 km and to have an average dislocation on the order of 25 cm. Such a hypothesis is of obvious importance to our block motion study because it indicates rather large block motions at depths and horizontal ranges where the direct explosion effects are considerably diminished.

The earthquake triggering hypothesis has led to a great deal of debate between proponents of this idea and a competing hypothesis, most prominently put forth by Archambeau and Sammis (1970), Archambeau (1972) and Lambert, et al. (1972). The latter authors conclude that the seismic energy is due to the relaxation of tectonic stress around the weakened zone created by the explosion. In this hypothesis, the block motion associated with the earthquake-like component of the source is considerably more localized near the explosion hypocenter.

There have been attempts to resolve the controversy between proponents of the two hypotheses for the origin of the strong earthquake-like component of the source. One of the most convincing studies is that by McEvilly and Peppin (1972) and we will summarize the most important of their results in a later paragraph. First, however, we point out that several points made above tend to weaken the arguments for the earthquake trigger model proposed by Aki and co-workers. Most telling is the fact that Aki and Tsai (1972) use surface faulting and aftershock evidence to favor their hypothesis of earthquake triggering. However, they do not mention the strong evidence that the two are unrelated. This observation considerably weakens their arguments.

If the surface faulting is associated with a substantial release of tectonic stress on a large fault plane, it is hard to imagine why there are no aftershocks on this fault plane, or why the surface strain data indicate that the fault displacements are confined to a region within 1-2 km of the surface. On the other hand, if the observed aftershocks outline a fault plane on which an earthquake had previously been triggered, it is hard to explain why such a large shallow event has no surface expression.

The aftershock evidence taken alone seems to favor the Archambeau model of tectonic release due to the explosion produced fracture zone. Aftershock data is often used to infer the probable extent of the fault plane for the main event. One expects to find the initial aftershocks to occur in the regions of greatest stress concentration - in the vicinity of the ends of the fault. Successive aftershocks then adjust the stress field, relieving it in one place, but also causing a buildup of stress nearby.

The aftershocks studied by Hamilton and Healy (1969) migrated along a fairly well defined fault zone. The migration of aftershocks was outward from the explosion epicenter. This is consistent with the hypothesis that the main release of tectonic strain was right around the explosion. Then with passage of time, the stress readjustment migrates outward (via the aftershocks) until the region reaches an equilibrium state.

Let us look now at the study reported by McEvilly and Peppin (1972). These authors looked at broad-band seismic data for some fifty-one NTS explosions, fourteen NTS explosion collapse events, eight NTS explosion aftershocks and twelve natural earthquakes. The natural earthquakes occurred at roughly the same range (500-550 km) from the recording station (Berkeley) as the NTS events. The authors compared time signals

and spectra and drew the following conclusions pertinent to our study:

1. For periods greater than about 5 seconds, explosion and collapse events have nearly the same source time-space functions; that is, the explosion source dimensions are not significantly greater than the collapse dimensions.

2. Rayleigh wave spectra and waveforms of large and small explosions at the same site are very similar, even for periods as short as 2 seconds.

3. The Rayleigh wave spectra are similar for large and small explosions and collapse events from the same source region, but significantly different from spectra for shallow (<5 km) earthquakes in the same area.

4. From 1-3, it is concluded that the total explosion source has source characteristics of small dimension and short time functions relative to shallow earthquakes in the same region.

5. The earthquake-like component of the larger explosions (producing large Love waves and a noncircular Rayleigh wave radiation pattern) is caused by processes in the immediate source region.

6. The observed surface faulting, such as that on the BOXCAR fault, may be a passive response to the strong ground shaking.

In brief, McEvilly and Peppin found no evidence to support the triggering of an earthquake by the large NTS explosions. Their observations seem to support the alternate tectonic release mechanism proposed by Archambeau and colleagues.

With this we complete our description of the evidence for block motion associated with underground explosions at NTS. As we said at the beginning, the evidence is complex and certainly difficult to organize into a quantitative description of block motion. We will return to this evidence in a later section where we summarize our conclusions. First, however, we should look at the observations of non-NTS events.

2.4 BLOCK MOTION ASSOCIATED WITH UNDERGROUND NUCLEAR EXPLOSIONS OUTSIDE NTS

Let us now examine the observations of a number of non-NTS underground nuclear explosions, contrasting them to the NTS events to see what we can learn about block motion. The events to be discussed are: (1) the Mississippi salt dome explosion SALMON; (2) the Nevada event SHOAL; (3) the Amchitka events LONGSHOT, MILROW and CANNIKIN.

The SALMON event is interesting because salt is a material that is as close to being isotropic and homogeneous as can be found in nature. More important, this material is unique in being unable to support tectonic stresses. Therefore, a quite significant observation is that almost no Love waves were generated by SALMON or by the previous salt explosion GNOME (Archambeau, et al., 1966). The near-field data also indicates that very little shear wave energy was generated by the SALMON source (Eisler and Hoffman, 1966). The data from the salt dome explosions then support the hypothesis that the NTS explosions are accompanied by tectonic release.

The SHOAL explosion was detonated on 26 October 1963 in central Nevada. An earthquake of roughly the same magnitude occurred only 60 km away during the previous year (20 July 1962). These two events were compared by Lambert, et al., (1972) on the basis of far-field (hundreds to thousands of kilometers) ground motion recordings in an attempt to discover the similarities and differences between the two types of sources. These authors conclude that the SHOAL explosion is accompanied by tectonic stress release that is similar to that from the Fallon earthquake in orientation. They also conclude that this earthquake-like component of the source is located very close to the explosion hypocenter and does not represent a triggered earthquake at depth or appreciable horizontal range.

The events in the Aleutians were detonated in an area known for high seismicity. These events, particularly the very large yield CANNIKIN, excited a great deal of scientific and public concern about the possiblity of a destructive earthquake being triggered. Therefore, a considerable amount of work was done on the seismic aspects of these events. Most of the work of interest to us is summarized in papers by Willis, et al. (1972), Engdahl (1972), Toksöz and Kehrer (1972), Romig (1972), Perret (1972), Dickey, et al. (1972) and Morris, et al. (1972). All appear in the December 1972 issue of the Bulletin of the Seismological Society of America.

The studies of the CANNIKIN and MILROW events all point toward the same conclusion. The earthquake-like effects of these events are similar to those from NTS events except that they are at a lower level. This seems to be due to the relatively low level of ambient tectonic stress at the Amchitka test site. The main conclusions are summarized by Engdahl (1972) and are listed below:

1. Amchitka lies above one of the world's most active seismic zones; yet no earthquake activity occurs on the Island proper.

2. Fault displacements produced by MILROW were significantly less than displacements from the same-size events at the Nevada Test Site.

3. Analysis of surface waves from MILROW and CANNIKIN indicates a relatively low level of tectonic strain release (Toksöz and Kehrer (1972)).

4. Earthquake-like aftershocks associated with MILROW and CANNIKIN were fewer and less widespread than those from many large NTS explosions.

5. *In situ* studies of stress in shallow drill holes suggest that a relatively low state of stress exists in the surface rocks on Amchitka, even in areas near faults (Carr, *et al.*, 1971).

2.5 EVIDENCE FOR BLOCK MOTION ASSOCIATED WITH CRATERING AND SURFACE EXPLOSIONS

There have been quite a number of atmospheric, surface and cratering nuclear explosion experiments carried out. These events are most nearly like the large surface bursts of primary interest for this block motion study. Unfortunately, we have found little published (seismological)data that can be used to deduce any special (compared to contained events) block motion behavior of these events. That is not to say such data do not exist, but we point out that most of these events were detonated before good ground motion data acquisition procedures were used. However, it has been noted (Press and Archambeau, 1962) that air explosions at NTS show little evidence of the near source generated Love and SH body waves that provide strong indirect evidence for block motion being associated with contained events.

2.6 SUMMARY – WHAT DOES THE SEISMOLOGICAL DATA TELL US ABOUT BLOCK MOTION

In the previous pages we have summarized the evidence for block motion that we have been able to find in the seismological literature. Now we will describe the conclusions to which we are led by this data. We admit that some of these conclusions may be controversial, but believe them to be supported by the weight of the evidence. Our format is to list the pertinent questions and follow with our answers.

What is the mechanism for generating the large earthquake-like seismic waves observed in the far-field?

Archambeau (1972) has developed a theory which not only proposes a mechanism for the generation of these waves but gives a quantitative description of them. We believe this explanation to be essentially correct. In the Archambeau theory, the nuclear explosion leads to creation of a weak zone due to the vaporization, crushing and cracking of the surrounding rock. If the region is tectonically stressed, the sudden introduction of this zone of reduced strength will cause a readjustment of the

tectonic stress field - the average tectonic stress in the region drops. However, local stress concentrations are sure to occur. From a distance, the energy release process is nearly identical to an earthquake with stress drop and fault dimensions of comparable size.

<u>What about the observed surface faulting?</u>

We believe the surface faulting represents a passive response to the strong ground shaking caused by the explosion. Most of the fault movement that has caused discussion is on faults that appear to be tectonically stressed, but weakly cemented due to the low lithostatic pressure near the surface. The direction of movement is then consistent with the tectonic stress, but is restricted to the region near the surface, probably less than a kilometer or so. If a number of explosions are detonated in the same region within a time interval that is short compared to the time for the buildup of tectonic stress, the fault movement should decrease, as has been observed. The key point is that little energy is released by this faulting.

<u>What are the observed explosion afterevents?</u>

There are two kinds of afterevents. One type are implosion events associated with the cavity collapse. These are located in the near cavity region and are of little interest for our study of block motion. The second type are earthquake-like and may occur at locations removed from the cavity. These we shall call aftershocks.

<u>Why do aftershocks occur?</u>

Just like earthquakes, the explosion causes a sudden readjustment of the tectonic stress field as the stress is relieved in the vicinity of the explosion-produced cavity. The new state is not one of stable equilibrium; there will be regions of concentrated stress. The stress adjusts toward equilibrium via aftershocks which may be viewed as triggered

earthquakes that may occur anywhere within the region where the tectonic stress state is significantly perturbed. The time for the region to reach a static equilibrium state may be measured in weeks or months.

One expects aftershocks to occur on local zones of weakness; that is, faults. The faults may be previously identified by their surface expression (e.g., the Rifle Range fault at Amchitka) or identified only by the previous occurrence of aftershock events (e.g., at Pahute Mesa, NTS). Observations indicate that the early aftershocks tend to occur in the portion of the fault nearest the cavity; that is, the region where the greatest stress concentrations are expected. With passage of time the aftershocks tend to migrate away from the cavity. This seems to indicate that the stress readjustment is occurring in a cascade fashion, each event relieving the stress in one place and causing a buildup at the next, though the average stress is continually decreasing.

Do explosions trigger earthquakes?

The after shocks are small earthquakes so the answer is partly yes. But if one means large energetic earthquakes (fault lengths of several kilometers for megaton events) triggered within seconds of the explosion, the answer seems to be no except in very unusual circumstances.

What is the key parameter controlling block motion?

All the block motion we have discussed here seem to be controlled by one key factor, the level of tectonic stress. Our seismological investigation has found evidence of block motion that is greatest at NTS and less at Amchitka where the level of stress is lower. We saw that this kind of block motion seems to be absent for an explosion in salt where the tectonic stress is essentially zero.

Are we missing something?

Perhaps. We said at the beginning (Section 2.1) that one type of block motion follows when the explosion overpressure causes differential displacements on pre-existing planes of weakness in the rock such as joints, faults and bedding planes. We have said almost nothing about this type of block motion, mostly because the evidence for it is masked and obscured by the block motion due to tectonic stress readjustment. It is likely that some of the "surface faulting" that is mapped post-shot (e.g., Figure 2.3a) is evidence of this type of block motion. In any case, we expect this type to be relatively localized compared to the tectonic stress induced block motion. Of course, in regions of low tectonic stress, it would predominate and become the block motion to be designed against.

When should block motion not occur?

Let us restrict our attention to the block motions caused by the presence of tectonic stress. Then the answer is simple: when the tectonic stresses are low. This may be the case in a region where the stress level is naturally low or in a location where the stresses have recently been relieved. However, note that the tectonic stress release by an explosion, according to our idea of the mechanism, affects only a rather small region, on the order of the elastic radius, about the cavity.

Can we make quantitative predictions of the block motion potential of a given site?

This is the key question and we will address it in the following section.

3. A QUANTITATIVE UNDERSTANDING OF BLOCK MOTION

What if we had to *quantify* our understanding of block motion at this moment? What would we do? First, we assume that the large surface bursts of interest will excite behavior that is not too different from that of contained explosions. The size and depth of the crater and crushed zone will be an important parameter to be accounted for.

As we have pointed out, there are two types of block motion: that associated with the presence of tectonic stress and that which is not. For the latter we believe a procedure suggested by Cooper (1973) gives reasonable estimates. He suggests that we collect the extremes of the observed data scatter for measurements of displacements due to explosions in hard rock. We then assume that the extremes represent the displacement in adjacent blocks of rock. Then he points out that since the observed scatter is about a factor of four, this procedure gives relative displacements of 1.5d, where d is the estimated displacement at a given range.

We recognize, as did Cooper (1973), that the procedure outlined above is overly simplified and leaves many questions unanswered. In particular, we may have difficulty extrapolating results to layered geologies. We merely point out that our seismological study does not help much with the problem.

We now turn our attention to block motion due to tectonic stress readjustment, the type to which nearly all the discussion of Section II was directed. There are three types of block motion that we have identified:

1. Motion associated with the release of tectonic stress because of the weak zone created by the explosion.

2. Passive motion on surface faults due to the strong ground shaking produced by the explosion.

3. Earthquake induced fault motion (aftershocks) associated with the return of the regional tectonic stress field to a stable equilibrium state.

Let us discuss these one at a time.

The first type is only marginally associated with the block motion of interest. The immediate release of tectonic stress because of the weak zone is not thought to involve large differential motion on a planar surface between two adjacent blocks of rock. The large shearing displacements are in a volume source region that has dimensions on the order of the elastic radius of the explosion. As we have mentioned, the theory developed by Archambeau (1972) seems a reasonable representation of this phenomenon. His theory allows direct computation of the displacements at any point in the elastic region.

The passive motion of surface faults has been mapped for quite a number of NTS events. At least for NTS, empirical laws can be drawn from these data which do a reasonably good job of predicting the fault displacements. The application of these laws could be tested by comparing to observations of the surface faulting for the several other areas at which tests were conducted. We point out that we believe the surface faulting to be representative of motion at only shallow depths where the lithostatic pressure is low, probably on the order of a few tens to hundreds of meters. Fault displacements may persist to greater depths, a kilometer or two, but would be expected to be considerably smaller than those at the surface. The surface displacements for the largest NTS explosions have been as much as a meter vertically and 10-15 cm horizontally at ranges of as much as several kilometers from the fault.

The aftershock induced block motion is perhaps the most interesting for our study. This motion has occurred at depth (up to 5 km) and some distance (up to 14 km) from contained

megaton explosions. The aftershocks seem to be evidence of sudden differential movement between adjacent blocks of rock. The question is, how large are these motions?

An order of magnitude estimate of the amplitude of the fault displacement can be made using empirical relations developed from studies of earthquakes. Kanamori and Anderson (1975) give the relation

$$\log S = M_s + 8.13 - \frac{2}{3} \log \left(\frac{\Delta\sigma}{\mu} \sigma_a \right) \quad ,$$

where S is fault area, M_s is surface wave magnitude, $\Delta\sigma$ is stress drop on the fault, μ is material rigidity and σ_a is the apparent stress which they estimate to be about half the stress drop.

Another useful relationship from Kanamori and Anderson (1975) is

$$\log M_o = 1.5 \log S + \log \Delta\sigma - 0.39 \ ,$$

for circular faults. In this case, M_o is the seismic moment:

$$M_o = \mu \ S \ \bar{D} \ ,$$

where $\bar{D}$ is the average dislocation on the fault.

Basham, et al. (1970) give M_s for some of the larger BENHAM aftershocks. These are as large as 4.3. Using this value and taking various values for μ and the stress drop ($\Delta\sigma$), we can estimate the range of values for the dislocation ($\bar{D}$). The pertinent numbers are given in Table 1.

Table 1

Estimates of fault parameters for BENHAM aftershocks

μ (kbar)	$\Delta\sigma$ (kbar)	S (km^2)	M_o dyne-cm	$\bar{D}$ (cm)
200	0.01	6.8	$10^{22.86}$	5.3
200	0.03	1.6	$10^{22.40}$	7.8
200	0.06	0.62	$10^{22.08}$	9.7
200	0.1	0.31	$10^{21.85}$	11.4
100	0.1	0.20	$10^{21.56}$	18.0

Everything about this estimate is crude. Still, for the largest event, $\bar{D}$ seems to be on the order of 20 cm or less for reasonable fault parameters. As a final estimate, let us assume an event with a moment of 10^{23} dyne-cm. Then, if μ = 200 kbar and S = 1 km^2, we find that $\Delta\sigma$ = 245 bars and $\bar{D}$ = 50 cm. This relative block movement of 0.5 meters seems to be a quite conservative upper limit for the aftershocks.

Let us now summarize the results of this section. For quantifying the block motion that is independent of the presence of tectonic stress, we have merely repeated the suggestion of Cooper (1973). For the tectonic release controlled block motion we find that there are really two kinds that seem to be of concern for the design of strategic structures. The first occurs almost simultaneously with the explosion, but is confined to a region near the surface where the lithostatic pressure is low. The second (aftershocks) can occur some days or weeks after the explosion, but may be at depths and ranges where the initial loading from the explosion was well below the design loading. Both of these types of block motion can be placed on an improved quantitative basis with some more detailed study of the data from past events. Our superficial study of the data indicates that for megaton sized events at depths of 1.1 - 1.4 km in a highly faulted and stressed region like Pahute Mesa the surface faulting may occur at distances

of up to 5-6 km from ground zero. The displacements at the surface may be as large as 1 meter.

For the aftershocks the size of the block displacements can only be estimated in an indirect fashion. We find that for the megaton events at Pahute Mesa this kind of block motion occurs at depths as great as 5 km and ranges as far as 14 km from the explosion. A crude estimate of the relative displacements indicates that a very conservative upper limit is about 0.5 meters. This limit could be considerably refined by more extensive study. In regions less highly stressed and less faulted than Pahute Mesa, the block motions are expected to be considerably less.

4. SUMMARY AND RECOMMENDATIONS

In our study of the seismological data, we have attempted to answer the following questions of importance for the block motion problem:

1. What block motion has occurred in association with contained underground nuclear explosions?

2. What are the important characteristics which control the susceptibility of sites to block motion?

3. What quantitative estimates of the block motion potential of a site can be made from studies of these events?

The answers to these questions appear throughout the material presented, but particularly in Sections 2.6 and 3.

Let us now discuss what we believe to be the important issues left unresolved. First, most of our understanding of the block motion from past events is qualitative. The quantitative estimates made in Section 3 are based on scant data and are quite crude. A more careful study could answer the following questions:

1. What is a good empirical scaling law for the surface fault motions associated with underground explosions? How well does it work for the Aleutian events, the Mississippi, Central Nevada and Colorado events? How about for the recent series of large Pahute Mesa events?

2. Concerning the surface fault motion, can better estimates of the motion at depth be made? The dislocation model technique used for one fault by Bucknam (1972) could be used for several faults. There may be information from drilling or other sources.

3. What is a good estimate for the fault motion associated with the aftershocks at NTS? How about in the Aleutians? The seismic data is available; all that is needed is a more careful analysis than that presented here.

4. What can be learned about block motion from surface explosions and cratering events, both nuclear and conventional? How does the block motion associated with these events correlate with what is expected from our experience with contained explosions? We simply did not address these questions here because we had little pertinent data at hand.

Our seismological study has concluded that the level of tectonic stress is a key parameter controlling the amount of block motion. Further, in stressed regions, the induced block motion occurs primarily along identifiable fault zones. (However, these may sometimes be difficult or impossible to identify beforehand.) Therefore, it is important to select regions of low tectonic stress. The first thing to look for is, of course, regions of low seismicity. Recall, though, that Amchitka is a site with low block motion compared to Pahute Mesa even though the seismicity is, superficially, much higher at Amchitka. However, the island seems to be decoupled from the very active zone that lies below. As a reconnaissance tool, seismicity should be estimated quite locally, taking depth into account.

Direct methods (using hydrofracture) for measuring the ambient tectonic stress are now being used with some success. Detailed site selection should include a series of such measurements to obtain the best possible estimate of the stress field. We also point out that well-developed geophysical methods such as magnetometer and reflection surveys are capable of mapping at least the large faults in a region.

Our objective in this study has been to critically examine the seismological evidence pertinent to the block motion problem and see what conclusions can be shown. For those questions that can be answered from information already available, we have tried to present the answers. We have then attempted to pose the important unresolved questions. By this effort we hope to provide a basis for decisions regarding future research and development efforts.

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